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Research Note
UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
OGDEN UTAH

U.S. Forest Service
Research Note INT-37
1965

LOW AIRSPEED DIFFERENTIAL PRESSURE INTEGRATING SYSTEM

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ABSTRACT

An instrument system for measuring small differential pressures in turbulent airstream flow can also measure airstream velocities within boundary layers, convection columns, and wind tunnels when turbulent flows range between 1 and 25 mph.

This paper describes an instrument system now used to measure small differential pressures in turbulent airstream flow. This system was developed to determine the velocity profiles in the low-speed wind tunnels at the Northern Forest Fire Laboratory at Missoula, Montana.

The system has also been useful for measuring velocities within boundary layers, convection column velocities, average wind tunnel velocity, and pressure drop across an orifice plate. These velocities have been measured in turbulent flows at speeds ranging from 1 to 25 mph.

DESIGN APPROACH

Measuring velocity profile by means of differential pressure (Δp) is not new. However, measuring such profiles at speeds less than 5 mph presents serious problems of instrument sensitivity and repeatability.

To achieve accuracy of 1 percent of the reading at 1.5 mph, the range of the measuring system must extend to approximately 2×10^{-5} inches of water. This precision cannot be achieved with instantaneous readout in turbulent airflow because the difference in total pressure, Δp_T, between two points may oscillate through zero and thus produce an ambiguous reading. The time average value of Δp_T does have a definite or repeatable value and may be obtained by integrating the fluctuating signal. In this system, a resistance capacitance circuit with a time constant of approximately 2.5 minutes performs the integration.

The difference in velocity between two points expressed as a fraction of free-stream velocity can be calculated from the difference in total pressure between the two points and the free-stream dynamic pressure with the formula:

$$\frac{v_2 - v_1}{v_o} = -1 + \sqrt{1 + \frac{(p_{T2} - p_{T1})}{q_o}} \qquad \text{(Eq. 1)}$$

where: v_1 = air velocity at center of tunnel

v_2 = air velocity at any other point in the same cross-sectional plane

v_o = free-stream average velocity

p_{T1} = total pressure at center of tunnel

p_{T2} = total pressure at any other point in the same cross-sectional plane

q_o = free-stream dynamic pressure.

Several characteristics of the differential pressure (Δp) method enhance its value for measuring air velocity. When making a velocity profile calibration, the differences in absolute velocity or total pressure between a reference point and a point in the test section must be obtained. Absolute measurements of velocity yield large numbers, which can cause inaccuracies since the differences in velocity may be smaller than can be measured accurately by instrument. However, a differential pressure measuring system automatically provides the difference in total pressure; hence, values obtained from it can be used in equation 1.

Another source of error inherent in devices for measuring absolute velocity, such as hot wire anemometers and rotating vanes, is drift of the average air velocity during the measurement. When measuring the differential pressure, Δp, drift of the average velocity has little effect on the ratio of $\frac{\Delta p}{q}$ where q is the dynamic pressure. Another advantage of the differential pressure system is its capability of being statically calibrated against a physical standard. In contrast, systems that measure air velocity directly must be calibrated in an airstream of known flow conditions. Operation of the differential pressure system has shown the data to be repeatable even after shutdown and restart of airflow through the wind tunnel. An example of data taken by this system at 1.5 mph is shown in figure 1.

The maximum differential pressure that can be measured by the system described here is 0.3 inch of water. This capacity is limited by the differential transducer. The minimum range is limited by the turbulence in the airstream and the drift of the integrator. Our experience indicates the minimum range is about 2×10^{-5} inches of water. Calibration of the transducer shows a linear relation of output voltage to input pressure. Integrated readings can be repeated every 3 to 4 minutes unless the preceding measurement heavily charges the capacitors in the integrator. Capacitors are self-charging; when heavily loaded, they require additional time to decay to an acceptable value. For this reason the dynamic pressure, q, for velocities greater than 2 mph should be read directly and not integrated.

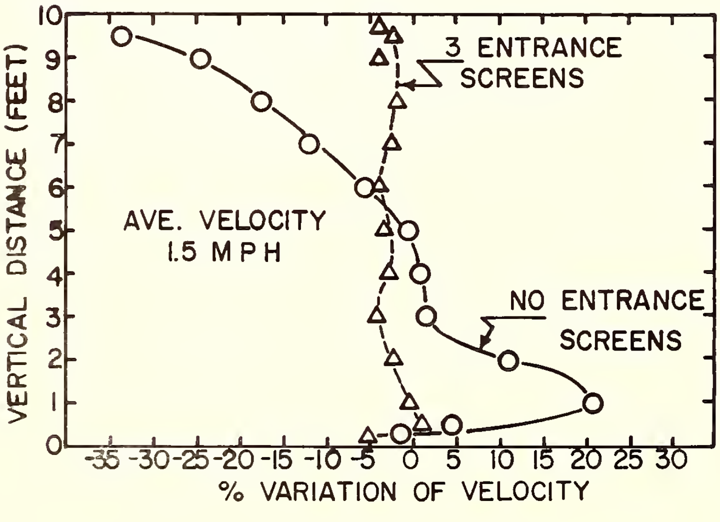

Figure 1.--Typical velocity profiles made in low-speed wind tunnel by the system described in this paper.

DESCRIPTION OF THE SYSTEM AND ITS COMPONENTS

The differential pressure measuring system now used at the Northern Forest Fire Laboratory (fig. 2) contains all of the components necessary for measuring low differential pressures, and includes a means of static calibration of the measuring components. These components and their functions are described below.

Probes.--Total pressure or Kiel probes measure p_{T1} and p_{T2}. The reference pressure probe, p_{T1}, is fixed at one location, normally the longitudinal centerline of the wind tunnel. The other probe, p_{T2}, is moved to the desired positions.

The dynamic pressure, q, is measured by a pitot-static probe located at the same wind tunnel cross section as the Kiel probes. The pitot-static probe should be located away from the tunnel walls but need not be in the center.

The size of the probes to be used depends somewhat on the velocity of the air and on the amount of air turbulence to be measured. For measuring velocities greater than 5 mph, size of the probe is not critical; but at speeds slower than 5 mph, good results were obtained by using Kiel probes made from $\frac{1}{4}$-inch copper tubing with a $\frac{1}{2}$-inch hood. Commercial probes are also suitable.

Snubbers.--A simple snubber may be used to dampen the pressure fluctuations in the tubes coming from the probes to the pressure switching box. Pinhole snubbers made from tubing connectors and masking tape are satisfactory. One or two snubbers in each line have proved satisfactory.

Pressure switching box.--The pressure switching box (figs. 3 and 4) is divided into high and low pressure sides and has high and low pressure manifolds to accept the input pressure lines. Each manifold is connected to the corresponding input post of the pressure transducer. An interconnecting line and an on-off

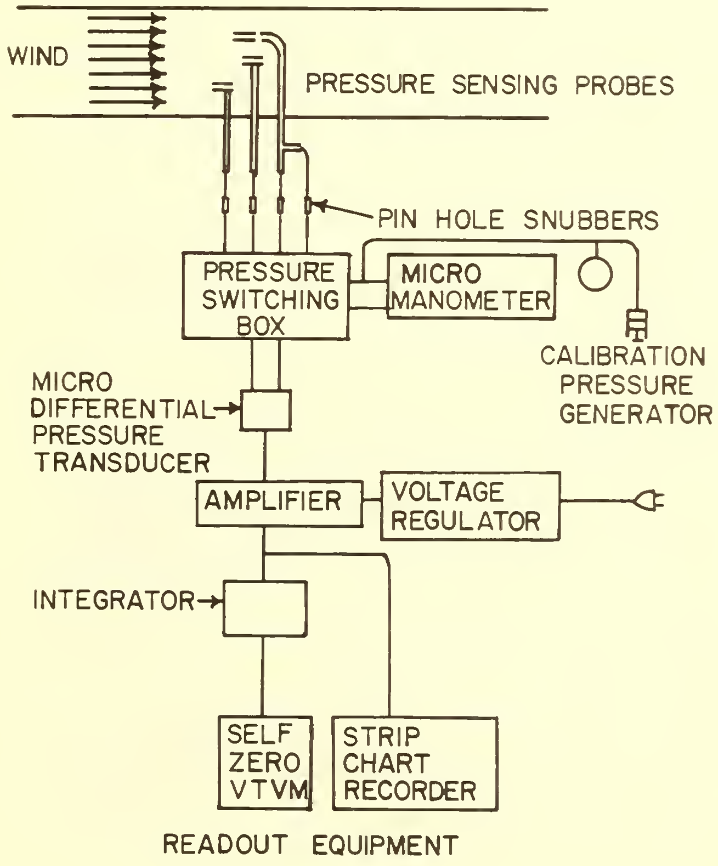

Figure 2.--Schematic of differential pressure measuring system.

valve are placed between the two manifolds. When open, the valve equalizes the pressure between the two manifolds and is used to zero the output of the transducer. The pressures are switched with on-off toggle valves. The input lines are attached with quick-disconnect plastic fittings.

Microdifferential pressure transducer and amplifier.--The transducer and amplifier (figs. 2 and 5) convert the differential pressure into an electrical signal. The transducer should be placed on a rigid table that will not yield under elbow pressure. Our system used a Decker Model 306-2F Transducer and Amplifier,[1] but equivalent equipment probably would be satisfactory. This transducer is a "no-flow" type that reduces the effect of line length and snubbers and prevents contaminated gases from reaching the transducer. The signal may be read directly on the amplifier meter or may be taken from the output jack to strip chart recorders or to an integrator. The 115-volt, 60-cycle power for the amplifier must be regulated.

Integrator.--The integrator box (figs. 5 and 6) contains the electrical components and switches needed to integrate the signal or to bypass it directly to the readout equipment. The time constant for a 5-megohm resistor and 25.5-microfarad capacitor is 2.12 minutes, but may vary with the components used. In operation, signals are integrated for 2 minutes.

Readout meter.--A self-zeroing high input impedence (10 megohm) vacuum tube voltmeter (fig. 5) with a minimum sensitivity of 1 mv full scale is required for readout of the integrated signal. A digital voltmeter probably could be substituted in this application, but a needle meter has been satisfactory. A center zero meter would be desirable, but a two-position + or − switch is adequate. Our system uses a Hewlett Packard Model 412 A. An equivalent meter would be satisfactory.

Calibration system.--A commercial micromanometer (fig. 4) is connected through the switching box to the pressure transducer. Our system uses a Flow Corporation Model MM 3. An equivalent manometer would be satisfactory. A plastic syringe in the high-pressure side of the system provides an adjustable positive pressure for both the micromanometer and the pressure transducer. A lead screw is attached to the plunger of the syringe for adjusting pressure slowly. A bottle is placed in the line to decrease sensitivity of the syringe.

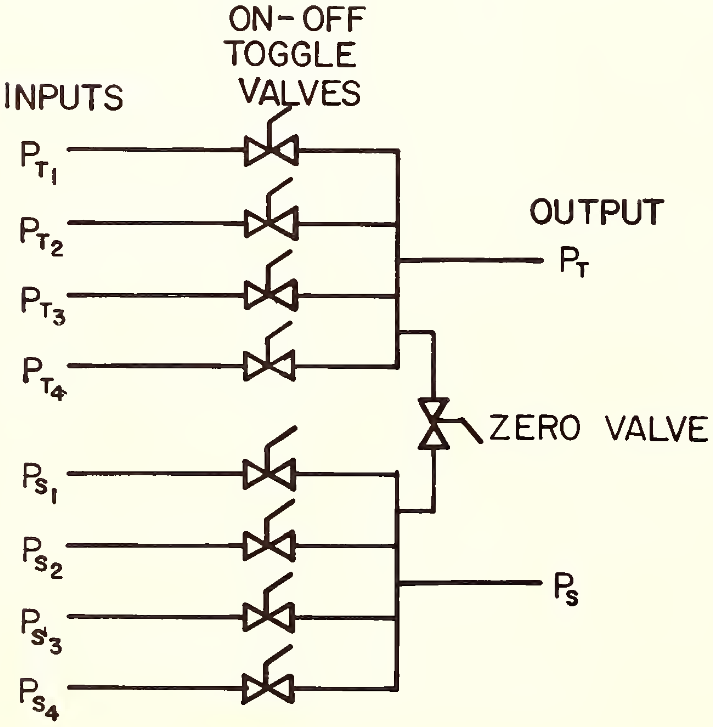

Figure 3.--Schematic of pressure switching box.

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[1] Brand names of equipment are used only for identification and do not constitute endorsement by the Forest Service.

It has not been possible to calibrate the system with less than 3×10^{-3} inches of water because a pressure less than this cannot be maintained for the required 2-minute integration period. The calibration curve (fig. 7) is linear through the calibration range and can be extended through zero. Calibration procedures are listed on page 7.

TROUBLEMAKERS

Measurement of weak signals requires certain precautions to prevent erroneous readings. Examples of sources of disturbances are listed below, with directions for obtaining best operation.

Electrical power fluctuations.--This point has already been mentioned but is reemphasized here. The electrical power source for the amplifier must be regulated for best performance of the equipment. Either transformers or electronic regulators can regulate power adequately.

Vibration.--The transducer and micromanometer must be placed on a heavy laboratory table. All pressure lines should be stable and free from oscillation when readings are taken.

Tubing routes.--Tubes should be kept as short as possible and should be kept close to each other so that they will be at the same temperature. Keep them away from lights that would heat the air inside only one tube. Avoid unnecessary vertical runs. A vertical tube that is at a different temperature from its mate will cause a serious error.

Temperature.--Most pressure transducers or their amplifiers are sensitive to temperature. Avoid installation in drafty rooms where temperature fluctuates frequently. Temperature of the airflow should be constant; otherwise, temperature corrections will be necessary.

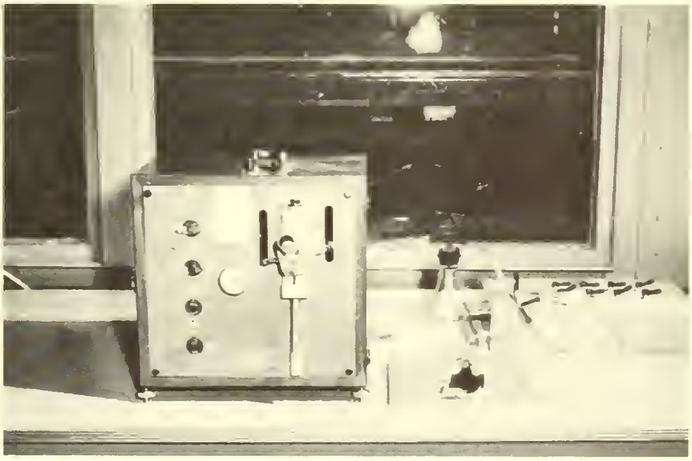

Figure 4.--Pressure calibrating system.

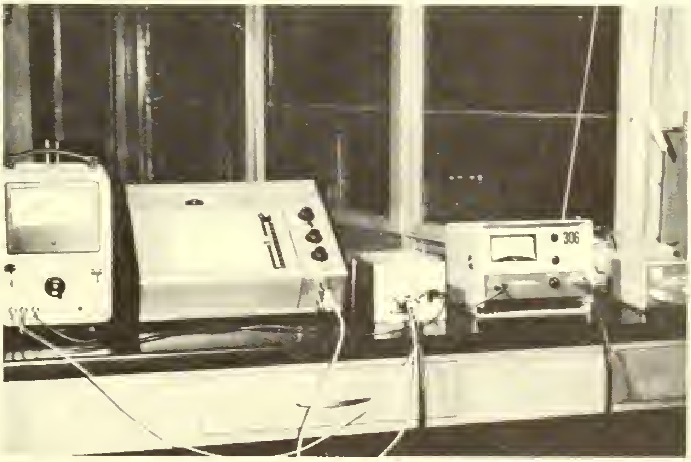

Figure 5.--Electrical pressure measuring equipment. From right to left: transducer, amplifier, integrator, strip chart recorder, and vacuum tube voltmeter.

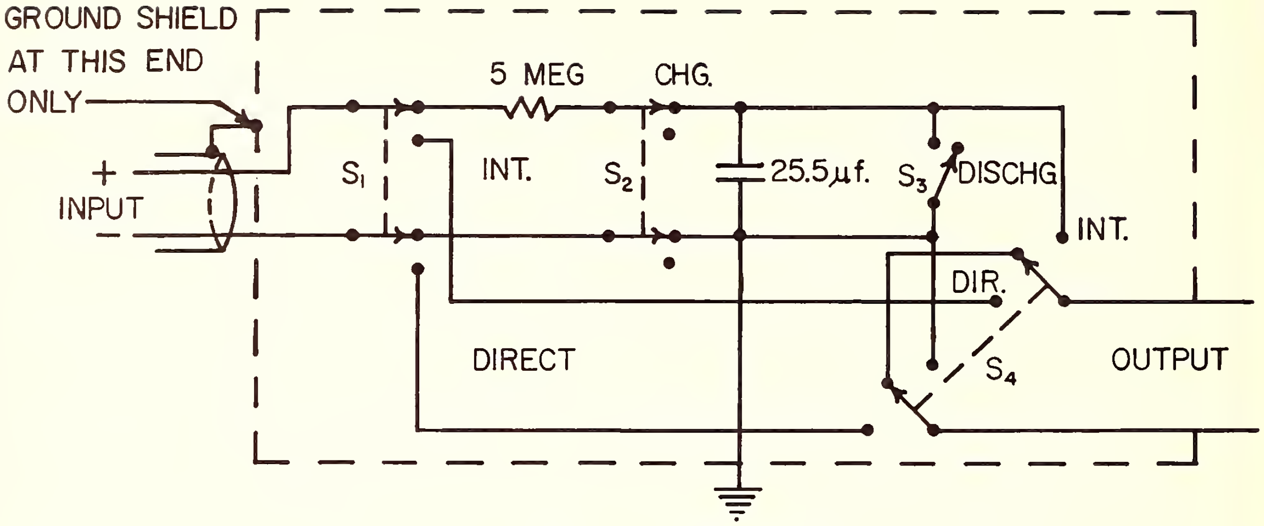

Figure 6.--Schematic of signal integrator.

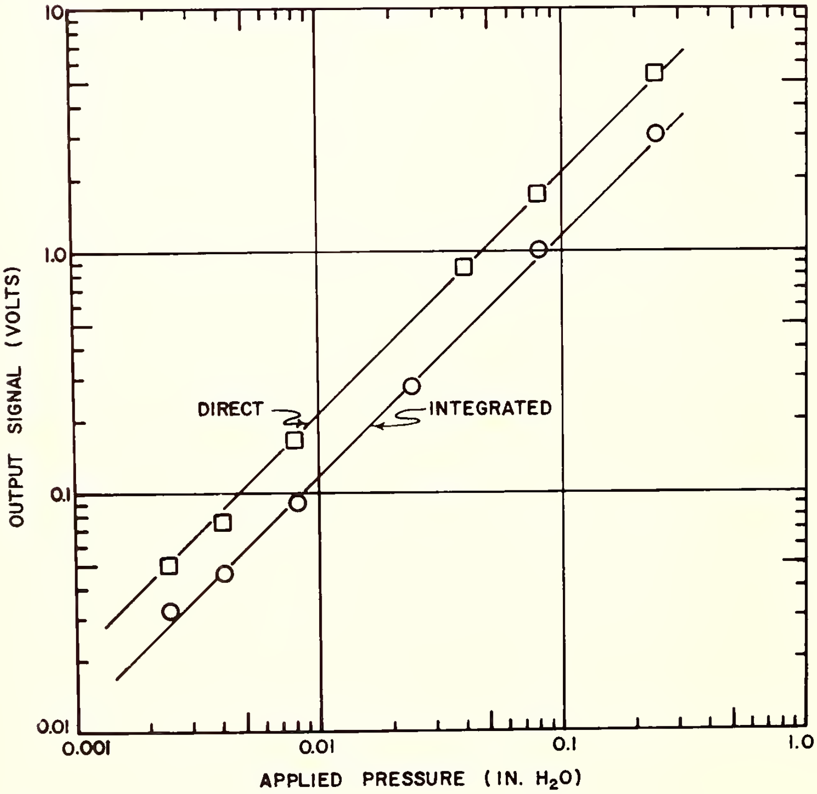

Figure 7. --Calibration curves for integrated or direct signal.

OPERATING PROCEDURES FOR WIND TUNNEL CALIBRATION

Warmup

Turn on transducer, amplifier, and output meter. Allow manufacturer's specified warmup time.

Calibration

1. On pressure switching box, open valves connecting micromanometer to transducer. Also open the zero valve.

2. Switch amplifier to most sensitive range and adjust amplifier meter to zero. Return amplifier range switch to "output" position.

3. Adjust micromanometer to zero.

4. Close zero valve on pressure switching box.

5. Using syringe, slowly increase pressure on transducer and micromanometer to 0.1 inch of water or whatever fluid the micromanometer contains.

6. On the integrator box, place the mode switch S 1 and the readout switch S 4 in "direct" position.

7. Read the output meter.

8. Using the following formula, calculate the calibration constant (C.C.). The specific-gravity correction relates the length of the column of manometer fluid to inches of water and is usually adjusted for the temperature of the fluid.

$$\text{C.C.} = \frac{\text{Voltage on meter}}{(0.1)\ (\text{specific-gravity correction})} = \frac{\text{Volts}}{\text{inches } H_20}$$

Setting air velocity

1. For the desired wind tunnel speed, compute the corresponding dynamic pressure, q, by the formula:

$$q = \frac{\rho v^2}{2g} \times 0.1922$$

where:

q = dynamic pressure--inches H_20

ρ = air density--lb/ft^3

v = air velocity--ft/sec

g = acceleration gravity--ft/sec^2

0.1922 = conversion from lb/ft^2 to inches H_20.

2. Multiply the desired dynamic pressure by the calibration constant to determine the voltage necessary for the desired velocity on the output meter.

3. On the pressure switching box, close the switches to the micromanometer and open the switches to the pitot-static tube. Close the zero switch.

4. With the integrator box switches still set for direct readout, observe the reading on the output meter. Adjust the air velocity until the output meter indicates the value of q calculated in step 2. The tunnel is now operating at the correct velocity, and calibration can begin.

Discharge capacitor

Note: The discharge switch S 3 should always be left in the closed position between readings.

1. On the pressure switching box, close all input switches and open the zero switch.

2. On the amplifier, re-zero the meter.

3. On the integrator, the discharge switch S 3 should be closed. Put the readout switch S 4 on "integrate," open the charge switch S 2, and put the mode switch S 1 on "integrate."

4. Open the discharge switch S 3 and increase the sensitivity of the readout meter until the needle comes upscale. It may be necessary to change polarity of the meter.

5. Observe the readout meter. If the integrator capacitor is discharged, the meter will remain stationary near zero mv and should be less than 0.1 mv. If the needle drifts, the capacitors are not discharged or the amplifier output is not zero.

6. To discharge the capacitors, close the discharge switch S 3 and open it again. After this has been repeated several times, the needle should remain stationary unless a large charge was previously on the capacitor--in which case more time will be necessary.

7. When the capacitors are discharged, the charge switch S 2 may be closed and the discharge switch S 3 opened. If the amplifier is truly zeroed, the output meter will remain stationary near zero ± 0.1 mv.

8. If the amplifier has drifted, it may be set more accurately by switching the integrator to direct readout and zeroing the amplifier on the readout meter.

9. When you are satisfied that the capacitor is discharged and the amplifier is at zero, close the discharge switch S 3 and prepare to integrate the desired signal without delay.

Integrating a signal

1. Choose the pressures to be integrated, either $p_{T0}-p_{S0}$ or $p_{T2}-p_{T1}$, on the pressure switching box. Close the zero valve.

2. On the integrator box, both the discharge switch S 3 and charge switch S 2 should be closed. The mode switch S 1 should be on "integrate" and the readout switch S 4 should be grounded.

3. Approximately 30 seconds after the zero valve has been closed (step 1), open the discharge switch S 3 and start a stopwatch at the same time.

4. When the stopwatch reaches 2 minutes, throw the readout switch S 4 to the "integrate" position and observe the readout meter. Record this reading after the first swing of the needle has stopped. Note that the capacitor will continue to charge slowly because the charge switch is still closed. If desired, the charge switch may also be opened at the end of 2 minutes.

5. After recording the reading (step 4), close the discharge switch S 3 and open the charge switch S 2. Open the zero valve on the pressure switching box, and close the pressure selecting valves. Discharge the capacitor as outlined in the section above.

Measuring dynamic pressure

If the wind tunnel holds a constant air velocity over long periods and the amplifier does not drift, the dynamic pressure need be read only every 2 to 3 hours.

For low velocities (1.5 to 2 mph), the dynamic pressure $p_{T0}-p_{S0}$ may be integrated as outlined above. For higher velocities, the signal for dynamic pressure will charge the capacitor to a value that will cause excessive discharge time. To prevent this, the signal may be read directly on the output meter, and the integrated value may be calculated for use in data reduction. To do this, of course, the ratio of integrated/direct reading must be found for a 2-minute integrated reading. This can be done easily with the calibration system. For our system, the ratio for integrated/direct = 0.576. This ratio will be different for each integrator. This ratio may also be used when setting the wind tunnel velocity at low speeds where it is desirable to integrate q to check the velocity.

When measuring any pressure, it is wise to take at least three readings and to check each one against the others. If the readings repeat well, the airflow fluctuations are consistent and the average should be used. If one reading is markedly different from the others, something may have caused a bad reading, or the air velocity may have a cyclic pattern that causes the average velocity to change with time. If consistent readings cannot be obtained at the same location, the airflow may be too turbulent to measure and damping screens should be installed in the mouth of the wind tunnel.